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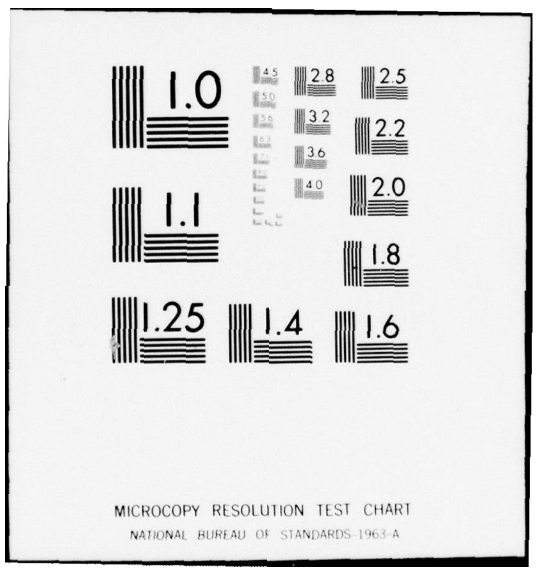
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DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Md. 20084

DYNAMIC STABILITY CHARACTERISTICS OF THE USS POINT LOMA (AGDS-2)

by

N. K. Bales

E. W. Foley

and

R. M. Watkins

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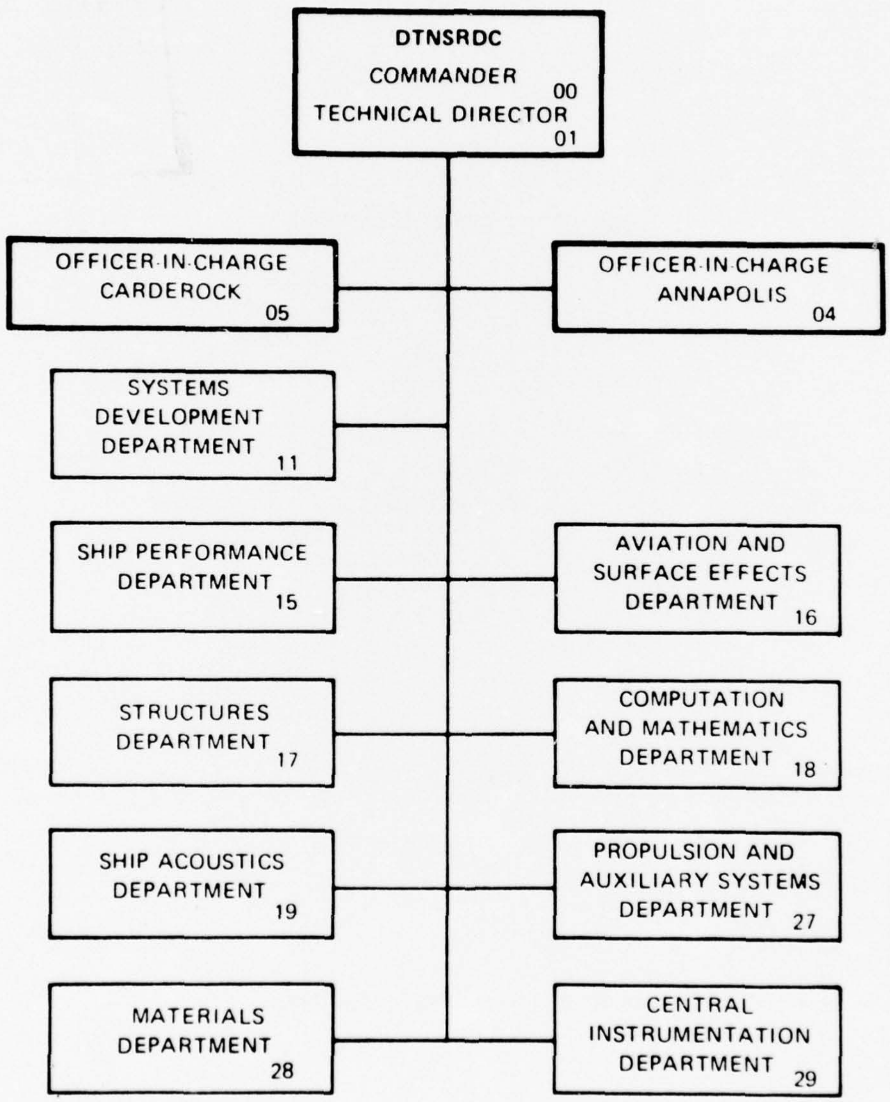

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The dynamic stability characteristics of the USS POINT LOMA (AGDS-2) are evaluated on the basis of a model experiment in waves. Two ballast conditions, one in which the ship has no freeboard at the stern and one in which the ship has 0.6 metres of freeboard at the stern, are considered. For both ballast conditions, the evaluation is limited to low-speed operation with the ship's well open to the sea. It is found that the POINT LOMA can become →

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ABSTRACT

The dynamic stability characteristics of the USS POINT LOMA (AGDS-2) are evaluated on the basis of a model experiment in waves. Two ballast conditions, one in which the ship has no freeboard at the stern and one in which the ship has 0.6 metres of freeboard at the stern, are considered. For both ballast conditions, the evaluation is limited to low-speed operation with the ship's well open to the sea. It is found that the POINT LOMA can become unstable in some environmentally-realistic wave systems when ballasted down to the zero-freeboard condition. In the 0.6 metre freeboard case, no instability is found.

ADMINISTRATIVE INFORMATION

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INTRODUCTION

The David W. Taylor Naval Ship Research and Development Center (DTNSRDC) was tasked to investigate the dynamic stability* characteristics of the USS POINT LOMA (AGDS-2). The POINT LOMA is a 133-metre long (between perpendiculars) ship with a stern-opening well and an antiroll tank. In the condition originally specified for the investigation, identified as the "17-foot well draft," the POINT LOMA is ballasted down to the point that there is no freeboard at the stern; and the well is open to the sea. Operation is restricted to low, e.g., minimum headway, speeds in this condition.

*Here <u>dynamic stability</u> refers to the ability of the ship to remain afloat in waves.

Subsequently, the investigation was extended to include a somewhat less severe ballast condition, identified as the "15-foot well draft." In this condition, the ship has 0.6 metres of freeboard at the stern. Again, evaluation was to be restricted to low speeds with the ship's well open to the sea.

No state-of-the-art analytical techniques are capable of resolving problems of this complexity, so a purely experimental approach was taken. The experiment and the results thereof are described and discussed hereinafter. Unless otherwise noted, all quantities are given at the scale of the prototype as obtained by Froude scaling of model quantities.

DESCRIPTION OF EXPERIMENT

A 1:29 scale model of the POINT LOMA was constructed. The model was built to sheer and fully appended. The well, well gate, and antiroll tank were modeled in detail; and the well beach was represented by a permeable fiber mat. The superstructure was crudely modeled in Styrofoam to reproduce its buoyant effect during any capsizing events which might occur.

The model was ballasted and rigged for self-propulsion in the DTNSRDC seakeeping basin described in Reference 1. Instrumentation to measure, record, and reduce data on waves in the basin and on the pitch, heave and roll of the model were provided. A video system to provide qualitative records of the experiment was also installed. Motion pictures were taken in a few, selected conditions.

The same experimental program was followed for each ballast condition. Initially, runs were made in low, regular waves at round-the-clock relative headings in 45-degree increments. For these runs, wave periods from 5 to 20 seconds were considered; and ship speeds were kept as low as possible to maintain headqay (usually two knots). Pitch, roll, and heave transfer functions were monitored.

The data base generated by the runs just described was evaluated to select critical conditions for further exploration. Wave data from the Hogben and

[1] Brownell, W.F., "A Rotating Arm and Maneuvering Basin," DTMB Report 1053 (July 1956).

Lumb atlas[2] was employed to assure that the wave parameters considered were viable in the context of the real environment. Statistics for year-round, worldwide operation were used. Wave height and period combinations expected to occur with probabilities of 0.001 to 0.0001 or less were taken as ideal upper limits. These low probability levels were chosen in view of the fact that ship survival was at issue. It was, however, recognized that some of the assigned limits would be unattainable due to the limitations of the facility employed for the experiment. Cases in which the ideal limits could not be met are pointed out in the subsequent discussion.

THE ZERO FREEBOARD ("17-FOOT WELL DRAFT") CASE

To represent the zero freeboard ("17-foot well draft") case, the model was ballasted to the conditions given in Table 1.

The initial series of runs at round-the-clock relative headings in low regular waves produced no evident instability, but did define some peaks in the monitored response transfer functions. The combinations of relative heading and wave period which produced these peaks were explored in regular waves of greater steepness than considered during the initial runs. Each combination so evaluated is described below.

In head waves, a wave period of 14 seconds produced a peak in the pitch transfer function. This condition was explored for wave steepnesses up to 1/36 (8.5 metre wave height*). No instability developed.

The heave transfer function exhibited a local peak at a wave period on the order of 8 seconds in all but beam waves. (It is of interest to note in this context that the length of an 8-second wave is approximately equal to the length of the POINT LOMA's well.) This local peak was explored in head waves where it was most prominent. Wave steepnesses to 1/18 (5.6 metre wave height) were attained, but no instability developed.

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[2] Hogben, N. and F.E. Lumb, "Ocean Wave Statistics," Her Majesty's Stationery Office, London (1967).

*SI units are used throughout the text. However, Figures 1 and 2 have scales in both metres and feet (0.3048 metres per foot); and can be used for quick conversions by readers who are accustomed to judging wave height in units of feet.

The rolling motion transfer function exhibited peaks in beam, bow and quartering waves. The peak in beam waves, which occurred at a 19-second wave period, appeared to be the most severe. This condition was explored for wave steepness of up to 1/72 (7.8 metre wave height) without any instability developing.

After the investigations in steep regular waves, random wave conditions were explored. Two wave spectra were used. One had a modal period of approximately 14 seconds (tuned to pitch resonance), and the other had a modal period of approximately 8 seconds (tuned to the local peak in the heave transfer functions). The 14-second modal period spectrum was used with significant wave heights up to 7.7 metres while the 8-second modal period spectrum was used with significant wave heights up to 5.1 metres. In this context, the 14-second/7.7 metre spectrum satisfied the 0.001 to 0.0001 probability of occurrence limits, but the 8-second/5.1 metre spectrum had a higher probability of occurrence. The wave statistics employed indicated that 8-second/7.1 metre spectra were expected to occur with a probability of 0.001, but 5.1 metres was the largest height which could be modeled with an 8-second modal period.

The random wave conditions just described were investigated in head, bow, and following seas. As a usual rule, 20 minutes of data were recorded. In bow seas, though, it proved impossible to maintain heading in the more severe conditions even when ship speed was increased to three knots. So, only 10 minutes of data were collected in this condition. It was thought that maintaining heading would be even more difficult in quartering seas, so this heading was not evaluated in the random wave series.

Large amplitude random waves caused frequent submergences of the after deck; and in the case of 8-second modal period seas from ahead, some water was shipped over the bow. In following seas, some rolling motion developed. It is likely, though, that this was due to heading deviations rather than a true instability. In any case, the model never appeared to be in danger of capsizing.

No beam seas were included in the random wave series just described because it was thought that the wave periods for which roll was appreciable were likely

to occur only as a result of a swell. The pure swell case was, of course, modeled by the series in steep, regular waves. To explore the possible influence of a swell tuned to the natural period of roll in greater detail, it was decided to generate a bidirectional wave system with one component representing a 19-second swell (tuned to the natural period of roll) and the second component representing a wind-generated sea.

The facility employed for the experiment will generate a bidirectional wave system only for the case of 90-degree opposition between the two wave components. This being the case, it was decided to make the wind-generated sea component come from ahead or astern and the swell come from the beam. It was further decided to use the same 8-second and 14-second modal period wave spectra used for the random wave series to represent the wind-generated seas.

The model survived the bidirectional wave system with wind-generated seas from ahead without instability developing. The same was true in the case of 14-second modal period seas from astern. With 8-second modal period seas from astern, though, a clear instability developed. The model took on an increasing heel angle down to the lee side of the beam swell. Rolling motion superimposed on the heel angle caused the leeward wing wall to submerge, and the situation was worsened by the seas from astern washing over the submerged wing wall and the cross deck forward of the beach. Ultimately the model lost stability and started to capsize.

This instability occurred when the significant height of the 8-second modal period following sea was as low as 4.6 metres and the steepness of the 19-second beam swell was as low as 1/125 (4.5 metre wave height). It should be noted that this condition does not necessarily represent a unique threshold for instability as there can be many "thresholds" associated with a bi-directional wave system. (If, for instance, the height of the sea had been fixed at 5.0 metres, instability might have occurred when the swell had a steepness of less than 1/125.) On the other hand, the condition does not indicate that instability can develop in a 19-second swell considerably less rare than that of 1/72 steepness which was taken as an upper limit. Further, as was noted above, the 8-second modal period seas were below the environmental limit even at the maximum significant wave height (5.1 metres) which could be modeled.

It was decided to explore the following sea/beam swell condition further by using a wave system which was slightly "detuned" with respect to the characteristics of the model. For these runs a sea with a modal period of 9.4 seconds and a swell with a period of 17 seconds were employed. The environmental limits for these wave conditions, again for 0.001 to 0.0001 probability of occurrence given year-round, worldwide operation, are on the order of 8 metres significant height for the sea and 1/60 steepness for the swell. The facility was capable of modeling a 17-second swell of 1/60 steepness or more, but the most severe sea of 9.4-second modal period which could be modeled had a significant height of only 5.8 metres.

Instability occurred in the detuned condition for a sea of 5.8 metre significant height and a swell of 1/54 steepness (8.4 metre wave height). The mechanism was as described above for the tuned case.

All of the occurrences of instability described above took place under normal experimental conditions. An additional occurrence resulted from nonstandard experimental practice, and it proved to be rather revealing regarding the stability characteristics of the model. In the course of a series of demonstration runs, a bidirectional wave system consisting of an 8-second swell of 1/34 steepness (2.9 metre wave height) from the beam and an 8-second modal period sea of 2.3 metre significant height from the stern was modeled. Instability occurred. It was found that the model had started this run with a list of more than 1.5 degrees due to water which had collected inside the shell during the preceding demonstration runs.

Subsequently, some of the conditions in which instability had been observed previously were repeated; and it was found that the occurrence of instability was strongly influenced by small initial angles of list. With the model carefully trimmed, the tuned bidirectional wave system (19-second swell from the beam and 8-second modal period sea from the stern) had to be modeled at a severity near its limits (environmental in the case of the swell and facility in the case of the sea) to cause instability. Specifically, the steepness of the 19-second swell was 1/72 and the 8-second modal period sea had a significant height of 5.1 metres. By contrast, the model had previously exhibited instability in the tuned, bidirectional wave system when the steepness of the swell

was 1/125 and the significant wave height of the sea was 4.6 metres. During these previous runs, initial lists of a fraction of a degree had, in accord with normal procedure in seakeeping experimentation, been englected. Obviously, though, they were not negligible in the case of the POINT LOMA model.

Some further notes regarding the experimental procedure followed when the model became unstable are in order. For most such events, the model was physically restrained when it became evident that a capsize was imminent. This was done to prevent possible damage to the instrumentation and running gear aboard the model and thereby allow the experiment to continue uninterrupted. Near the end of the experiment, though, some runs were made in which the capsizing events were allowed to run their full course. Then the model inclined only to the point at which the superstructure entered the water and developed a sufficient righting moment to produce stability. The model would remain in this attitude for protracted intervals, but ultimate capsizing never occurred.

It is now in order to summarize and, to the extent possible quantify the results just presented regarding instability of the POINT LOMA model. Instability was found to occur only in bidirectional wave systems with a swell from the beam and a sea from the stern. This instability resulted in capsizing to the lee side of the beam swell. The capsizing events which occurred were not "complete" in the sense of the model rolling through 180 degrees. Rather, the righting moment which was generated when the superstructure entered the water limited the final inclination of the model to the order of 50 to 60 degrees.

Capsizing appeared to result from combined rolling and heeling and the associated accumulation of water on deck. The largest total inclination (combined heel and roll) from which the model recovered was 18 degrees. Heeling was the predominant factor. It accounted for up to 15 degrees inclination.

The wave system parameters which led to instability were sensitive to small (less than one degree) initial lists. With the model perfectly trimmed, a severe wave system tuned to its natural frequency characteristics (19-second swell of 1/72 steepness and 8-second modal period sea of 5.1 metre significant height) had to be generated to cause capsizing. With the model slightly out

of trim, instability occurred in a detuned wave system (17-second swell of 1/54 steepness and 9.4-second modal period sea of 5.8 metre significant height) and in a less severe tuned wave system (19-second swell of 1/125 steepness and 8-second modal period sea of 4.6 metre significant height).

THE 0.6 METRE FREEBOARD ("15-FOOT WELL DRAFT") CASE

To represent the 0.6 metre freeboard (15-foot well draft") case, the model was ballasted to the conditions given in Table 2.

The initial series of runs at round-the-clock relative headings in low regular waves gave rise to no evident instability. However, these runs did define peaks in the pitch, heave, and roll transfer functions. Pitch transfer functions were generally similar to those found for the zero freeboard case. Again, the only evident peak occurred in head waves of 14 second period. In all but beam waves, the heaving characteristics of the model were similar to those found for the zero freeboard case, e.g., the local peak in 8-second waves was again present. In beam waves, though, the heave transfer function exhibited a prominent peak at 9 seconds. This phenomenon had not been found for the zero freeboard case. The peak values of the roll transfer functions were 30 to 40 percent lower than in the zero freeboard case, and occurred at a wave period on the order of 14 seconds as compared to 19 seconds for the zero freeboard case.

The lower peak value of the roll transfer function was obviously to the advantage of the 0.6 metre freeboard condition, but the decrease in the period at which this peak occurred indicated that considerably steeper waves were possible within the assigned environmental limits. So, the likelihood of instability developing in beam waves and in bidirectional waves with a component from the beam (in which capsizing had occurred for the zero freeboard condition) was not easily assessed. It was, accordingly, decided to begin the exploration of possible instability in these conditions. Further, in deference to the sensitivity to list which had been found for the zero freeboard ballast condition, it was decided to explore the effects of initial list. The POINT

LOMA's operating instructions state that angle of list be 3 degrees or less,*
so a 3-degree list was adopted for the model experiment.

Initial exploratory runs were made with zero list in 9-second (maximum heave) and 14-second (maximum roll) regular waves from the beam. A steepness of 1/23 was attained at each of these periods. This steepness, corresponding to wave heights of 5.5 metres in the 9-second case and 13.3 metres in the 14-second case, was near the assigned environmental limits in both cases. The model remained stable in these waves though the amplitude of roll in the 14-second case reached 8.7 degrees. This was about twice the amplitude attained in the analogous wave condition when ballasted to zero freeboard at the stern.

Random seas from the beam were also explored at zero list. A wave spectrum model with a modal period which scaled very close to the 14-second natural period of roll was not programmed for the wavemaker bank required for beam waves. Among the available wave spectrum models, one with a scaled modal period of 12 seconds and considerable energy at both 9 and 14 seconds was thought to be most promising. This spectrum was modeled to a significant wave height of 6.4 metres. This height is below the established environmental limit by about 3 metres, but was the largest within the capability of the facility. The model gave no indication of instability in this wave spectrum though it was very wet and difficult to control.

With respect to initial list, the first matter which had to be addressed was whether the model would be in greater danger of developing instability due to a weather or a leeward list. In the zero freeboard condition, a list to leeward would have been the obvious answer. At the 0.6 metre freeboard, though, the model was considerably stiffer in roll; and did not exhibit the tendency to heel to leeward that had been observed in the zero freeboard condition. So, it was considered necessary to explore both possibilities in moderate depth.

Runs were made in beam swells and in bidirectional waves with a swell from the beam and a sea from astern with the model listed 3 degrees both

*This limit has since been reduced to one degree.

to weather and to leeward of the beam swell. A 14-second period (tuned to roll resonance) was used for the beam swell, and an 8-second modal period sea (tuned to the local peak in the heave transfer function) was modeled from astern. In the bidirectional case, the sea was modeled to a significant height of 6.1 metres and the swell to a steepness of 1/40 (7.6 metre wave height). Attempts were made to exceed these magnitudes, but the model was uncontrollable even when speed was increased to 4 knots.

The runs just described encompassed conditions as closely analogous as possible to those which caused capsizing in the zero freeboard case, but they produced no indication of instability. Runs were also made in the analogous conditions with zero list and in the same condition (19-second swell from the beam and 8-second modal period sea from the stern) which caused capsizing in the zero freeboard case. Again, no instability developed. Comparison of these various runs did, however, indicate qualitatively that the model shipped more water with a list to the weather side than with an equal list to leeward. Hence, it was decided to perform subsequent runs with a 3-degree list to the weather side.

Quartering and bow headings were explored for seas of 14-second modal period. These conditions seemed potentially critical because they would excite roll resonance as well as inducing large pitch and heave motions. In view of the oblique-heading control difficulties which had been experienced in the zero freeboard case and the fact that control was generally more difficult in the 0.6 metre freeboard case, it was decided to approach these conditions by first establishing the maximum wave height in which control could be maintained at 2 knots and then assessing stability at this wave height. The runs in bi-directional waves had, in fact, already established the relevance of a "controllability threshold" for the 0.6 metre freeboard case.

In bow seas of 14-second modal period, marginal control could be maintained for significant wave heights up to 6.1 metres. In quartering seas, the corresponding maximum was on the order of 5.2 metres. Instability did not develop at either of the oblique headings.

To conclude the experiment, it was decided to briefly explore the effect of altering metacentric height at the 0.6 metre freeboard ballast condition.

Accessible ballast weights were moved upward to reduce the scaled metacentric height to 1.6 metres. This increased the natural period of roll to 16.5 seconds.

At the reduced metacentric height, runs were made in a bidirectional wave system composed of a 16.5-second swell from the beam and an 8-second modal period sea from the stern. Initial lists of 3 degrees to both the leeward and weather sides of the beam swell were considered. The swell was modeled to a steepness of 1/47 (9.0 metre wave height), and the sea was modeled to a significant height of 4.3 metres. The model shipped large quantities of water, perhaps slightly more with the list to weather than that to leeward, but no instability developed.

DISCUSSION OF RESULTS

It appears viable to hypothesize that the capsizing events which the POINT LOMA model experienced in the zero freeboard condition resulted from total loss of transverse righting moment due primarily to massive water shipment and attendant loss of waterplane area. If such is the case, it is evident that this total loss of righting moment did not occur for the 0.6 metre freeboard condition in roughly analogous environments or even when an initial list of 3 degrees was arbitrarily imposed. Though very little literature regarding dynamic stability exists at the current state-of-the-art, some substantiation for the viability of the hypothesized capsizing mechanism can be found.

The U.S. Coast Guard is presently conducting a rather extensive investigation of dynamic stability. Some results of this investigation are published in References 3 and 4. The Reference 3 work pertains to high speed operation in quartering and following waves, i.e., for conditions in which the ship is subject to low or zero wave encounter frequencies. Three capsizing mechanisms

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[3] Paulling, J.R. and Paul D. Wood, "Numerical Simulation of Large-Amplitude Ship Motions in Astern Seas," Proceedings of SNAME Technical and Research Symposium S-3 (June 1974).

[4] "Evaluation of Current Towing Vessel Stability Criterion and Proposed Fishing Vessel Stability Criteria," various authors, USCG Reports CG-D-69-75, CG-D-3-76 and CG-D-4-76 (Feb 1975 - Jan 1976).

are found to occur: low frequency resonance, pure loss of stability on a wave crest, and broaching. The Reference 4 investigation is less restrictive in point of operating conditions, but is limited to small vessels. It is found that a vessel in beam waves can capsize as a result of rolling into the waves, shipping water, and experiencing a slowly increasing angle of heel. Reference is made to descriptions of a like phenomenon described in the foreign literature as "pseudo-statical heel."

The capsizing mechanisms described in Reference 3 do not apply here. This follows from the fact that the low speeds considered do not produce significant wave energy at near-zero encounter frequencies. On the other hand, the mechanism described in Reference 4 for a small vessel in beam waves is very similar to that which the POINT LOMA model experienced. It is also of interest to note that Reference 4 indicates that whether heeling occurs to weather or to leeward is a function of ship characteristics. This supports the fact that the present investigation found list to leeward to be more critical in the zero freeboard condition, but list to weather to be more critical in the 0.6 metre freeboard condition.

In the context of the hypothesized mechanism of instability, some rather subjective observations regarding transverse stability which were made during the experiment bear mention here. When the model was ballasted to the zero freeboard condition, it was observed that inclining it to an angle of 15 to 20 degrees appeared to cause loss of stability. This observation correlated rather well with the fact, cited above, that the largest inclination from which the model recovered without capsizing (while ballasted to represent the zero freeboard condition) was 18 degrees.

When the model was ballasted to represent the 0.6 metre freeboard condition, an attempt was made to establish a comparable threshold angle for loss of transverse righting moment. In this condition, though, an unequivocal value could not be obtained. It seemed that the superstructure, which entered the water at an inclination of about 30 degrees, prevented the occurrence of total loss of transverse righting moment. Further, it can be noted that, during one of the runs made in tuned, bidirectional waves at the 0.6 metre freeboard condition, the model was manually pulled to a weather-side inclination of 24 degrees; and that it recovered without hesitation from this inclination.

When the metacentric height was reduced at the 0.6 metre freeboard condition, inclining the model indicated that it became very soft at an angle of about 26 degrees. However, the model did not definitely become unstable. Again, it appeared that the superstructure began to stiffen the righting moment before a definitive threshold was reached.

These results offer some crude support for the hypothesis put forward to account for the capsizing of the POINT LOMA model in the zero freeboard case, and for its failure to capsize in analogous conditions when ballasted to represent the 0.6 metre freeboard case. It is unfortunate, in this context, that the cited results are subjective. For future experiments of this type, it would be desirable to provide some mechanism to measure the force or moment required to produce a given inclination.

The hypothesized mechanism of capsizing places great importance upon the ship's transverse-plane hydrostatic characteristics. Computation of these characteristics for a ship with a well is nontrivial. In the case of the POINT LOMA, the fact that the aft freeboard is so small that slight inclinations cause loss of waterplane area further complicates the procedure. It was these factors which motivated the brief exploration of a reduced transverse metacentric height in the 0.6 metre freeboard condition.

Two recommendations follow from the foregoing comments on ship hydrostatics. It would be desirable to perform an inclining experiment with the prototype POINT LOMA to ensure that the modeled transverse metacentric height was correct. For future model experiments with well ships ballasted as radically as the POINT LOMA, attention should be given to locating the vertical center of gravity instead of or in addition to adjusting metacentric height. (This approach was not viable in the case of the POINT LOMA model because the weight of the model exceeded the capacity of the apparatus used to determine the location of the center of gravity. Indeed, this recommendation imposes something of a general dilemma in that a rather large model is needed to represent local details such as the well beach and the antiroll tank used in the case of the POINT LOMA model. The best solution would seem to be to increase the capacity of the apparatus needed to measure the center of gravity location.)

Two other uncertainties associated with extrapolation to the prototype require discussion here. One, suggested by the preceding comment regarding the need for a "rather large" model, is that some uncertainty exists regarding the validity of Froude scaling of ship well hydrodynamics. At the present state-of-the-art, though, no alternatives are available; and it is generally thought that using a large model minimizes the influence of those phenomena which are not amenable to Froude scaling.

The second uncertainty is associated with the low-speed course keeping characteristics of the ship as compared to those of the model. It is understood that, during the operation of concern here, the prototype POINT LOMA is controlled by independent use of its twin screws. The model, on the other hand, was controlled by rudder action. Since rudder action is relatively ineffective at low speeds, it appears likely that the prototype would be capable of maintaining course in more adverse environments than the model was. In any case, it cannot be said that the low-speed course keeping characteristics of the prototype were scaled. This factor was probably more important in the 0.6 metre freeboard case than in the zero freeboard case since control difficulties were more prevalent in the former case.

Development of a model control system based on independent use of twin screws is probably within reach of the state-of-the-art in experimental naval architecture. The developmental effort required was not, however, within the time or cost framework of the POINT LOMA investigation. In view of the large number of prototype operations which require position or course keeping at very low speeds, the development of such a model control system is a worthwhile objective.

Finally, there is an unresolvable dilemma associated with any investigation of the type being reported here which must be discussed. The essential thrust of this investigation was to establish conditions in which a "disaster" would occur. Such an investigation can consider only a finite number of independent parameter combinations. Thus the possible outcomes are that the disaster occurred in some conditions or that the disaster did not occur in some conditions. The former result is a viable conclusion, but the latter not: the fact that the disaster did not occur in some conditions does not imply that it cannot occur.

Here the "independent parameter combinations" in question are those of wave characteristics and ship-to-wave relative heading. It is possible that, in the 0.6 metre freeboard case, critical conditions for capsizing were not modeled due to either human oversight or to the physical limitations of the experimental apparatus. At least it can be said that every effort was made to avoid errors due to human oversight, and to minimize the effect of physical limitations.

The preceding discussions of ship hydrostatics, scaling of ship well hydrodynamics and of low speed ship controllability, and of the dilemma associated with the failure to obtain any capsizing events in the 0.6 metre freeboard condition direct attention to the uncertainties associated with the POINT LOMA model experiment. Within the constraints imposed by these uncertainties, considerable guidance for operation of the POINT LOMA can be derived from the results of the experiment. This matter is addressed in the immediately-following section.

OPERATIONAL GUIDELINES

Two assumptions must be made for purposes of establishing operational guidelines. First, it is assumed that the ballast characteristics modeled for the experiment (see Tables 1 and 2) correctly represent those of the prototype. Second, it is assumed that the mechanism most likely to cause the POINT LOMA to become unstable and capsize* at either ballast condition is total loss of transverse righting moment; i.e., the same mechanism hypothesized to have caused the capsizing which occurred during the model experiment in the zero freeboard case. The guidelines will, of course, apply to low speed operation with the stern gate open in the zero freeboard ("17-foot well draft") and 0.6 metre freeboard ("15-foot well draft") ballast conditions.

Initially, it should be pointed out that causing the POINT LOMA model to become unstable and capsize in the zero freeboard case was not easy. The

*Though ultimate capsizing in the sense of a 180-degree roll was prevented by the superstructure at model scale, it is thought that unequivocal use of the term capsizing is in order here because the prototype superstructure is unlikely to provide intact buoyancy equivalent to that provided by the Styrofoam superstructure used on the model.

model survived an array of severe wave conditions which any one ship is rather unlikely to encounter in its life cycle. Further, the capsizing occurred at a ship-to-wave relative heading (sea from astern) which would likely be avoided by good seamanship when at all possible in a given tactical situation. In the 0.6 metre case, the same comment with respect to wave conditions applies even though capsizing never occurred.

Figure 1 is intended to provide additional perspective regarding these comments on the wave environment. This figure, derived from Reference 2 for worldwide, all-season operation, compares the 0.001 and 0.0001 probability of occurrence wave environments taken as ideal upper limits (and frequently attained) for this investigation with the most frequently occurring wave environments. As can be seen the most frequently occurring waves are lower by factors of two to three than the "limiting" waves for low modal periods, but converge with the low probability of occurrence waves as modal period increases. This occurs because waves of very high modal period are generically rare.

It is of interest to evaluate the wave conditions in which the POINT LOMA model became unstable in the context of Figure 1. It will be recalled that instability occurred only in bidirectional waves having a component from the beam and a component from astern. Figure 2 superimposes--very crudely--the wave conditions which led to capsizing in the zero freeboard ballast condition on the wave environment characteristics given by Figure 1. The critical areas include capsize events which occurred with the model slightly out of trim as this situation is considered to be realistic for the prototype. (For reference purposes, the wave conditions during the demonstration run which caused capsizing with the model significantly out of trim are shown as isolated points in Figure 2. These data are not included in the analysis which follows.) The swell from the beam is characterized in terms of significant wave height and modal period because the available environmental data do not admit an unequivocal distinction between sea and swell.

The probability of occurrence of the "Following Component" area defined by Figure 2 is about 0.0323. That of the "Beam Component" area is about 0.0013. Given the reasonable assumption that the two components are independent, the probability of their joint occurrence is, hence, on the order of 4.2×10^{-5}.

The probability of the two components occurring jointly and at 90-degree opposition in direction, though it cannot be defined from the available wave statistics, would obviously be even smaller.

Though the likelihood of the wave environment which was found to cause capsizing in the zero freeboard condition occurring is small, there is some finite risk of its occurring on any given voyage. The same is true of the wave environments found to be most severe in the 0.6 metre freeboard case. And, of course, severe or even critical wave environments not evaluated during the POINT LOMA experiment may arise at either ballast condition.

To aid the operator in evaluating the severity of given wave conditions as a function of ship orientation with respect to the waves, Figure 3 presents the ship response transfer function data derived from the POINT LOMA model experiment.* During the experiment, these results were used to select adverse conditions. In the present context, they are intended for operator guidance in selecting benign conditions. For instance, the conditions which led to capsizing in the zero freeboard case are marked by a pronounced roll resonance in 19-second beam waves and a local heave peak in 8-second following waves; and the combination is obviously to be avoided.

More generally, the assumed mechanism of capsizing (total loss of transverse righting moment) implies that avoidance of heavy rolling is an important consideration. Rolling will be minimized in head and following waves though it will not usually go to zero as implied by Figure 3 due to the directional spreading normally associated with realistic wave spectra. Since operation in following waves with the stern gate open is undesirable in the context of the POINT LOMA's mission, operation in head waves is evidently desirable from the viewpoint of avoiding heavy rolling, If, however, the waves have significant energy at periods on the order of 8 or 14 seconds, heave (in the 8-second case) or pitch (in the 14-second case) will be significant; and could prove

*It is strongly emphasized that these transfer functions are of less than normal laboratory quality. They were crudely defined to provide experimental guidance in a situation where a priori analytical results could not be obtained. Here they are presented solely for purposes of operational guidance, and should in no way be construed as a laboratory-quality characterization of the responses of the POINT LOMA.

deleterious to the mission. In a case involving 8-second waves, a change of heading in the direction of bow seas might, then, be desirable in either of the ballast conditions under consideration here. The same could prove to be the case for 14-second waves when in the zero freeboard ballast condition. In the 0.6 metre freeboard ballast condition, though, turning to a bow heading in 14-second waves would excite roll resonance.

The discussion just given focused on rolling motion in the context of possible loss of transverse righting moment. Initial list and heeling must be addressed in the same context. The results of the experiment indicate that an initial list can increase the likelihood of instability developing. This indicates that ballasting-down operations should be conducted in such a manner as to minimize the list taken on. It is, of course, recognized that the operator will not be able to define the zero list condition unequivocally; and may be constrained to operate with a small but discernible list. In the latter circumstance, the list should be taken to the weather side when in the zero freeboard condition but to leeward when in the 0.6 metre freeboard condition.

It will be recalled that wave-induced heeling was the major component of the total inclination which led to capsizing during the POINT LOMA model experiment. This phenomenon was observed to occur only in capsizing cases, i.e., in bidirectional waves (sea from astern and swell from the beam) in the zero freeboard ballast condition. However, the state-of-the-art literature previously cited (see Reference 4) indicates that the phenomenon can occur in pure beam waves. Generally, then, it can be surmised that avoiding conditions which induce heavy rolling (as discussed above) will also minimize the likelihood of experiencing significant wave-induced heeling.

Wind loadings must also be addressed with respect to heeling. For a steady wind, the effect would appear to be similar to that of a list. In the presence of gustiness, unknown dynamic effects could be introduced. The state-of-the-art literature does not provide sufficient data on ship profile wind drag coefficients to admit quantitative assessment of this matter even for a steady wind. Generally, though, it would seem desirable to take the guidance offered above with respect to list to apply as well to wind-induced heel. When the wind is coming from the same direction as the waves, the list and heel

recommendations will be compatible in the 0.6 metre freeboard condition; but incompatible in the zero freeboard condition. In the latter condition, a "lesser of evils" choice will be required.

The importance of maintaining transverse trim during ballasting-down operations has already been cited. Another important matter in the context of these operations is maintenance of adequate metacentric height. As has been pointed out, this parameter is critical in cases of instability due to loss of transverse righting moment. Extraneous free surfaces will reduce metacentric height and thence have a deleterious influence on the ship's stability. It follows that all tanks which must be filled to ballast to a given condition should be carefully pressed-up.

Ultimately, then, the thrust of the guidance offered here is that loss of transverse metacentric height and extreme angles of transverse inclination (vector sum of roll, heel and initial list) should be avoided in order to maintain stability. The POINT LOMA model experiment offers crude quantification of "extreme" in this context. In the zero freeboard condition (with a transverse metacentric height on the order of 1.0 metre) the largest total inclination from which a recovery was made was 18 degrees. In the 0.6 metre freeboard condition (with a transverse metacentric height of 2.0 metres) recovery was made from an inclination of 24 degrees. The latter figure is obviously not definitive; and the former is subject to some equivocation in the context of modeling errors. At the least, thought, the comparison reinforces the basic results of the experiment in indicating that the POINT LOMA is considerably less likely to become unstable in the 0.6 metre freeboard condition than in the zero freeboard condition. It follows that operation in the zero freeboard ballast condition should be avoided whenever possible.

CONCLUSIONS

These conclusions apply to the USS POINT LOMA (AGDS-2) operating at very low speed with well gate open in the zero freeboard ("17-foot well draft") ballast condition as defined by Table 1 and in 0.6 metre freeboard ("15-foot well draft") ballast condition as defined by Table 2.

The experiment reported here demonstrated that, in the zero freeboard ballast condition, the POINT LOMA model became unstable in some environmentally realistic wave conditions. While questions may reasonably be raised concerning the validity of the modeling with respect to well hydrodynamics and to low speed controllability, it is thought that these factors are of considerably less importance than the observed instability in a situation involving ship survival. It is therefore concluded that the POINT LOMA can become unstable when operating among waves in the zero freeboard ballast condition.

In the 0.6 metre freeboard ballast condition, the POINT LOMA model did not become unstable in any operating condition evaluated. The full range of environmental conditions which the prototype might experience could not be modeled, and it is possible that errors in judgment led to selection of subcritical conditions even within the restrictions imposed by the experimental apparatus. Further, the scaling uncertainties cited above in the context of the zero freeboard results are not as easily neglected in a situation such that instability did not occur. These factors preclude the possibility of drawing a reasonably unequivocal conclusion regarding the stability of the POINT LOMA when operating among waves in the 0.6 metre freeboard ballast condition.

In general, it appears that prudent seamanship, intelligent utilization of the operational guidelines presented here, and avoiding the zero freeboard ballast condition when at all possible will reduce the likelihood of the POINT LOMA becoming unstable to an acceptable minimum.

RECOMMENDATIONS

It is recommended that an inclining experiment be conducted with the POINT LOMA to ensure that transverse metacentric height was correctly modeled for the experiment reported herein. In addition, it is recommended that the POINT LOMA conduct operations in the 0.6 metre freeboard ("15-foot well draft") ballast condition in preference to the zero freeboard ("17-foot well draft") ballast condition when at all possible. It is also recommended that this report, especially the "OPERATIONAL GUIDELINES" section, be used by the POINT

LOMA's officers as an aid to seamanship in avoiding conditions which could lead to instability and subsequent capsizing.

The POINT LOMA model experiment was a pioneering effort in the area of dynamic stability for DTNSRDC, and the project was complicated by the unusual configuration and operational mode of the hull investigated. It therefore seems appropriate to mention here that the preceding "DISCUSSION OF RESULTS" section includes several laboratory-level recommendations for future work involving comparable elements. Among the matters touched upon are wave generation, model control at low speeds, ballasting procedure, and a mechanism to measure transverse righting moment.

TABLE 1 - ZERO FREEBOARD ("17-FOOT WELL DRAFT") BALLAST CHARACTERISTICS

Parameter (Units)	Magnitude
Draft at forward perpendicular (metres)	9.1
Draft at sill (metres)	12.1
Displacement in salt water (tonnes)	17,008
Longitudinal radius of gyration (metres)	35.8
Transverse metacentric height* (metres)	0.9 to 1.1
Natural period of roll (seconds)	19

*Metacentric height was difficult to measure accurately because of its small model-scale magnitude (about 3.5 centimeters) and the fact that moving the inclining weight caused variations in waterplane area.

TABLE 2 - 0.6 METRE FREEBOARD ("15-FOOT WELL DRAFT") BALLAST CHARACTERISTICS

Parameter (Units)	Magnitude
Draft at forward perpendicular (metres)	9.9
Draft at sill (metres)	11.6
Displacement in salt water (tonnes)	17,200
Longitudinal radius of gyration (metres)	35.8
Transverse metacentric height (metres)	2.0
Natural Period of roll* (seconds)	14

*The period of roll was adjusted to match that measured on the prototype in the 0.6 metre freeboard ballast condition.

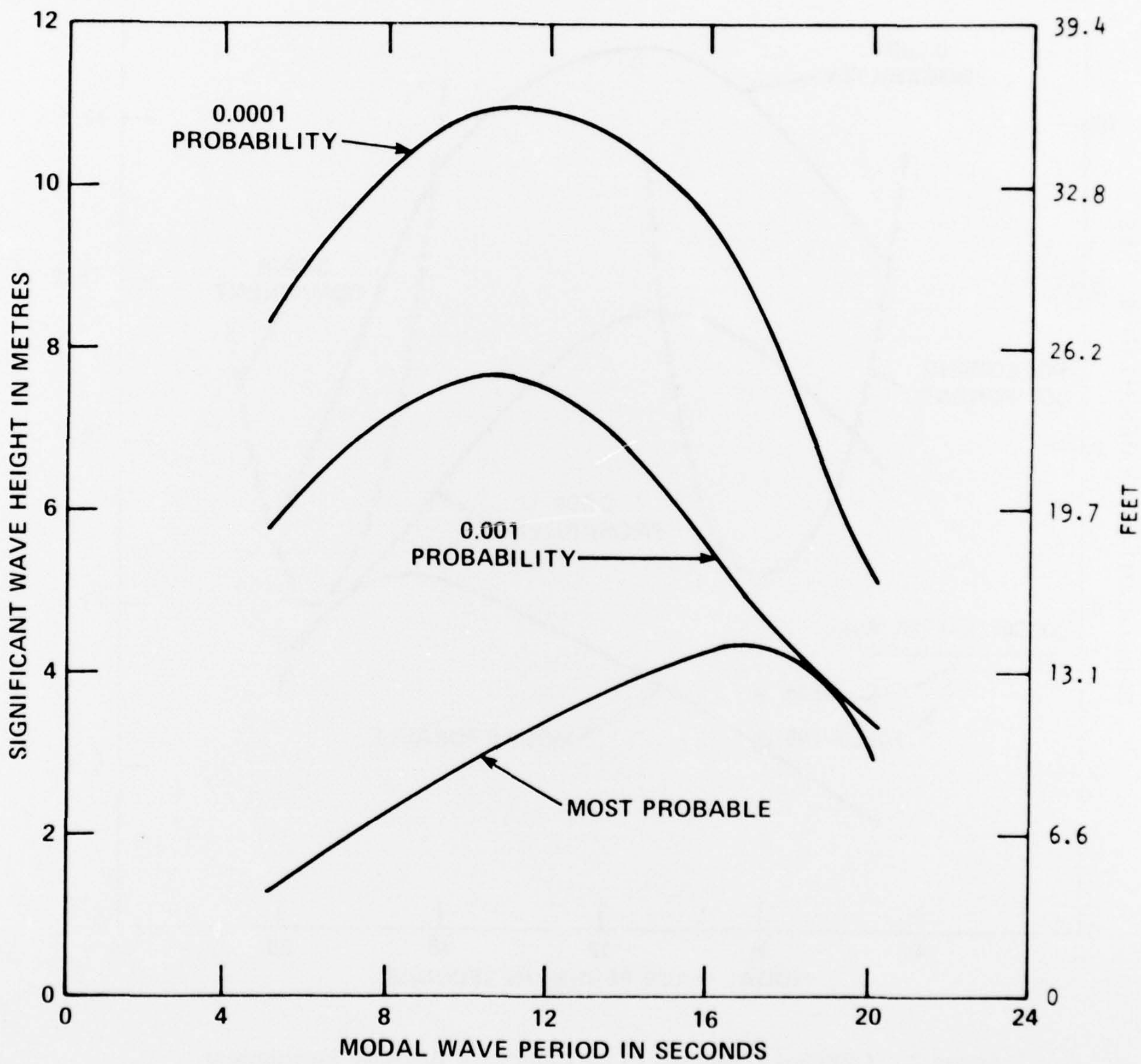


Figure 1 – Characteristics of the Wave Environment

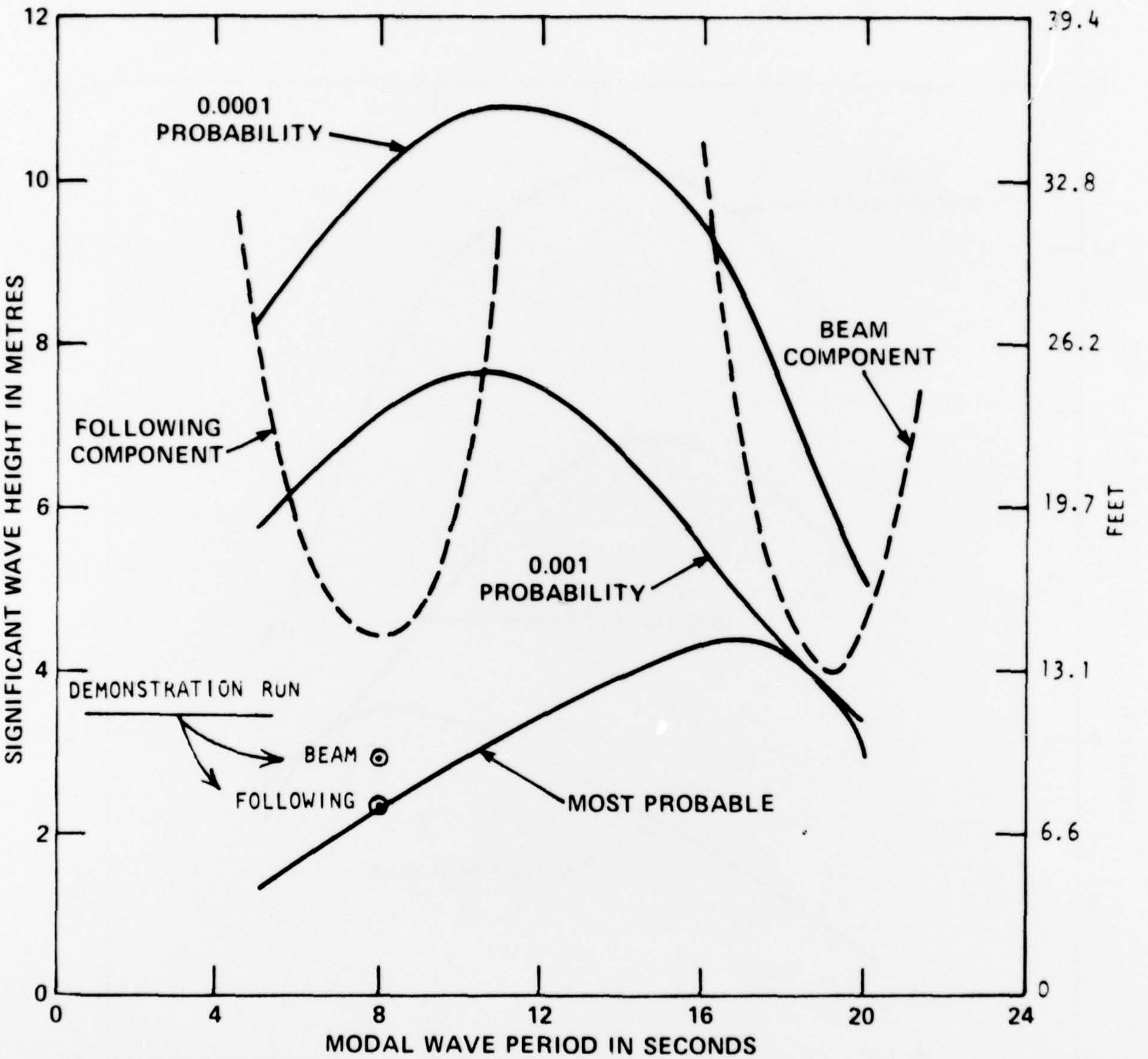
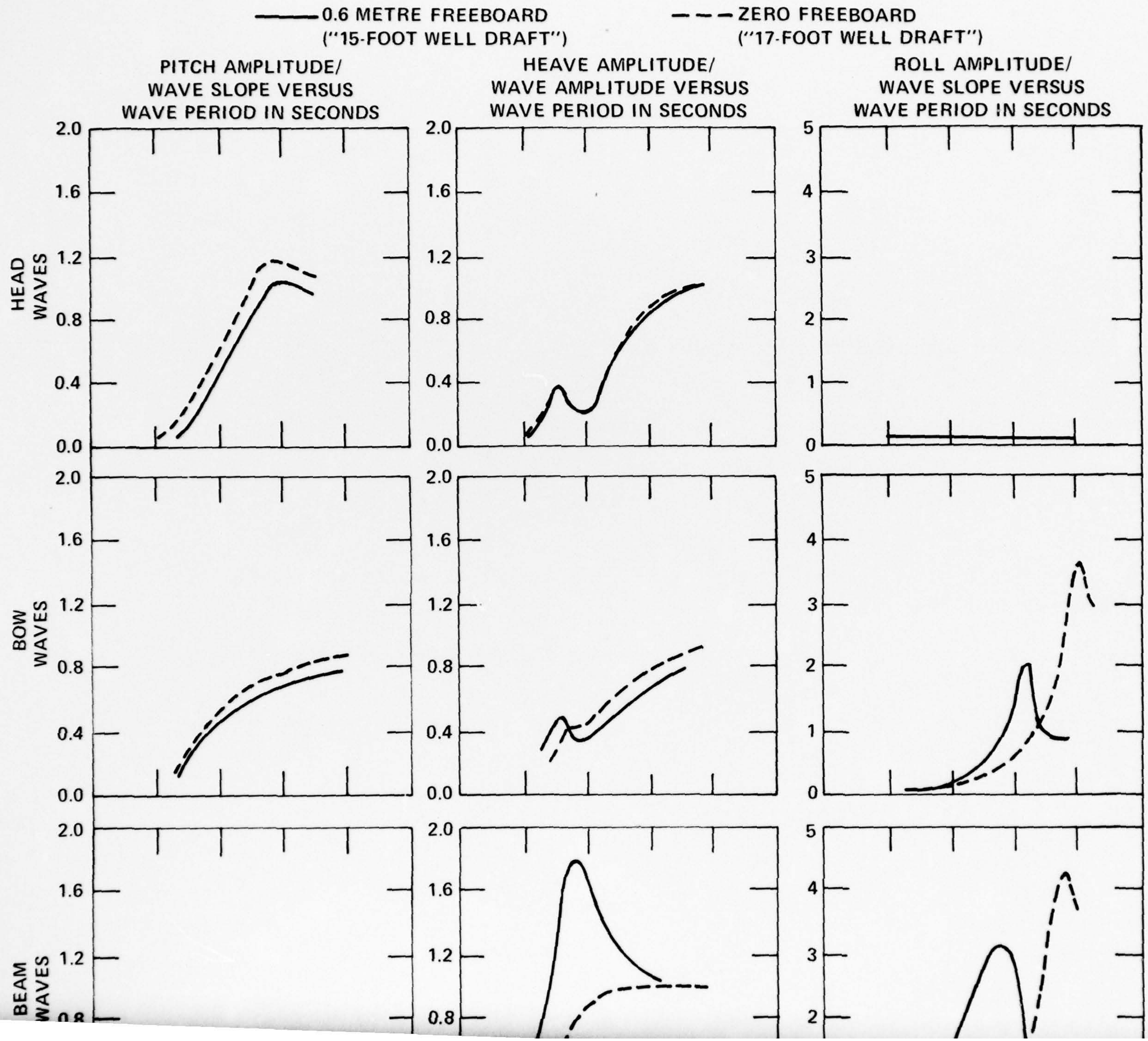


Figure 2 – Capsizing Conditions in the Context of the Wave Environment



0.6 METRE FREEBOARD
("15-FOOT WELL DRAFT")
ZERO FREEBOARD
("17-FOOT WELL DRAFT")
PITCH AMPLITUDE/
WAVE SLOPE VERSUS
WAVE PERIOD IN SECONDS
HEAVE AMPLITUDE/
WAVE AMPLITUDE VERSUS
WAVE PERIOD IN SECONDS
ROLL AMPLITUDE/
WAVE SLOPE VERSUS
WAVE PERIOD IN SECONDS
HEAD WAVES
BOW WAVES
BEAM WAVES
2.0
1.6
1.2
0.8
0.4
0.0
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4
3
2
1
0

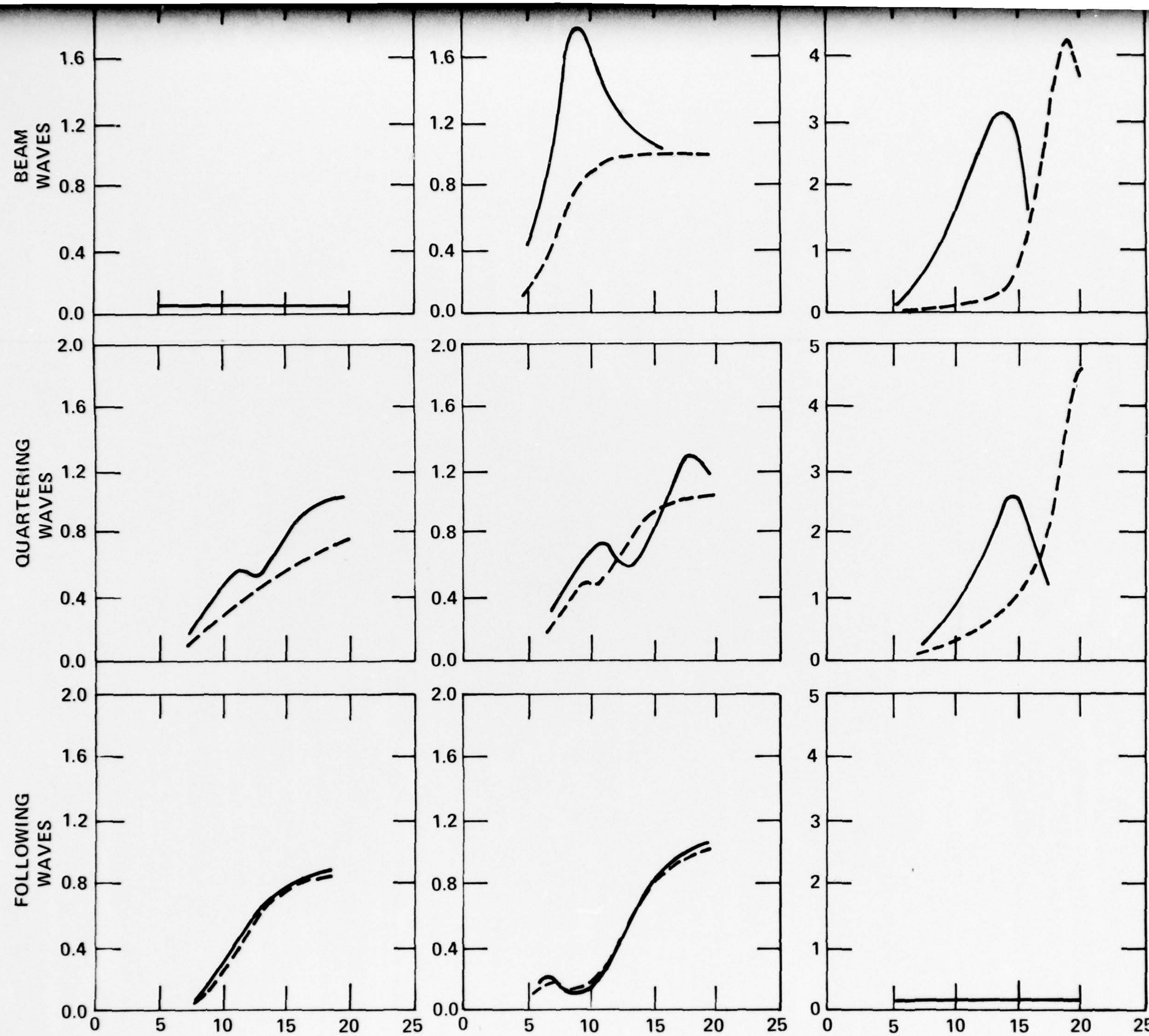

Figure 3 – Approximate Point Loma Transfer Functions

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